FLUOR

Introduction to data reduction

Michelson summer school
May 2001 session

Flagstaff, Arizona

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May 22nd, 2001

Outline

- Terminology
- Estimating coherence factors
- Deriving visibilities: calibration
- Assessing data quality

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- ✓ *Visibility :* $$V(\vec{B},\lambda)=\left|\frac{\int_{source} I(\vec{S},\lambda)\exp\left[-2i\pi\vec{S}.\frac{\vec{B}}{\lambda}\right]d^2\vec{S}}{\int_{source} I(\vec{S},\lambda)\,d^2\vec{S}}\right|$$

- ✓ *Coherence factor :* uncalibrated constrast of the fringes

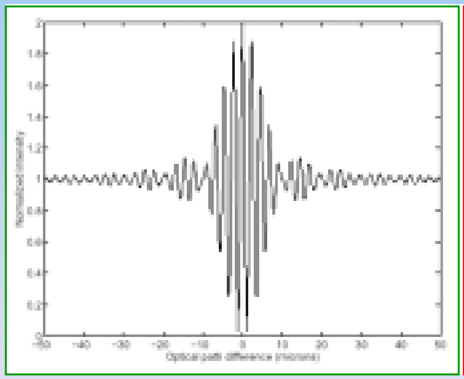
- ✓ *Transfer function :* ratio of expected visibility to measured coherence factor

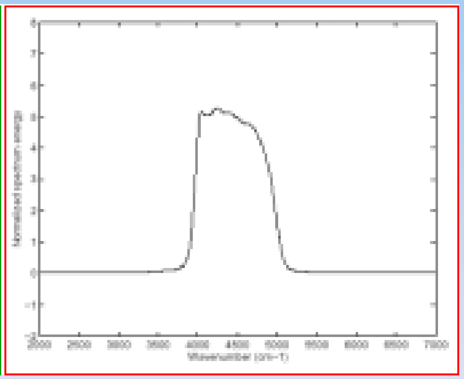
- ✓ *FTS :* Fourier Transform Spectrometer

Fourier transform

Scan

Intensity vs. x opd in µm





Spectrum B(σ)

$\sigma = 1/\lambda$ = wavenumber (cm^{-1})

K band : 4000 - 5000 cm^{-1}

x and σ are conjugate variables

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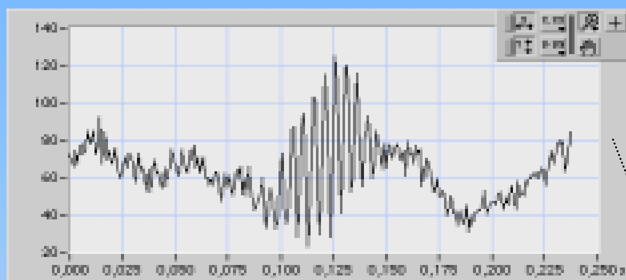
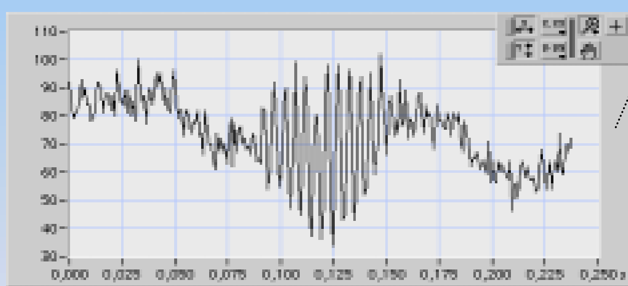
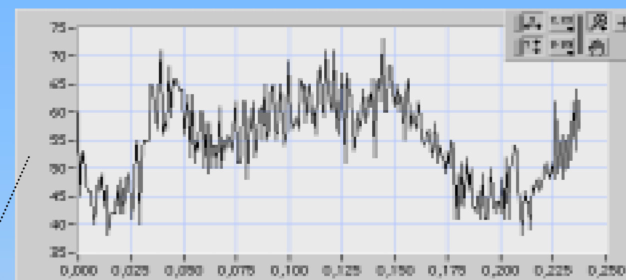
Expression of the FLUOR interferogram in the monochromatic case:

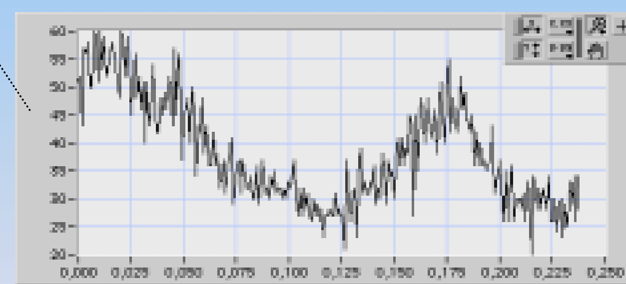
$$
\begin{aligned}
I^i(x,\sigma) &= P_A^i(x,\sigma) + P_B^i(x,\sigma) + 2(-1)^i \mu(\sigma)\sqrt{P_A^i(x,\sigma)P_B^i(x,\sigma)}\cos(2\pi\sigma x + \varphi) \\
&= \kappa_A^i(x,\sigma)P_A(x,\sigma) + \kappa_B^i(x,\sigma)P_B(x,\sigma) + \\
&\qquad 2(-1)^i \mu(\sigma)\sqrt{\kappa_A^i(x,\sigma)P_A^i(x,\sigma)\kappa_B^i(x,\sigma)P_B^i(x,\sigma)}\cos(2\pi\sigma x + \varphi)
\end{aligned}
$$





$$
\begin{pmatrix} I^1 \\ I^2 \end{pmatrix}_{LF} = \begin{bmatrix} \kappa_A^1 & \kappa_B^1 \\ \kappa_A^2 & \kappa_B^2 \end{bmatrix} \begin{pmatrix} P_A \\ P_B \end{pmatrix}
$$



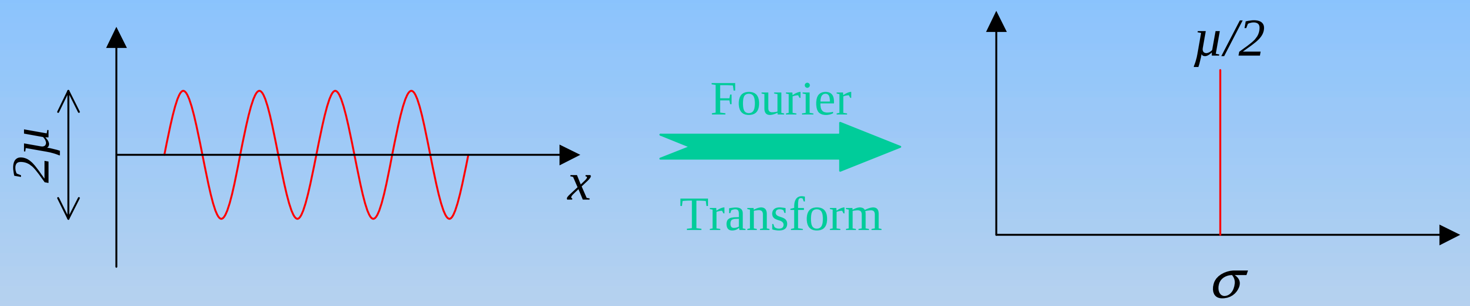


The κ matrix is estimated by blocking alernatively one of the beams of FLUOR and recording the signals in the unblocked photometric and two interferometric channels

Principle of the photometric calibration:

$$\mu(\sigma)\cos(2\pi\sigma x + \varphi + i\pi) = \frac{I^i(x,\sigma) - P_A^i(x,\sigma) - P_B^i(x,\sigma)}{2\sqrt{P_A^i(x,\sigma)P_B^i(x,\sigma)}}$$

Principle of the contrast estimation:



The fringe contrast is computed by integrating the spectrum

To avoid bias of the contrast modulus estimate by noise, the integration is performed on the power spectral density

Polychromatic case:

$$I^i(x) = \int_{band} I^i(x,\sigma)\,d\sigma$$

$$= \int_{band} P_A^i(x,\sigma) + P_B^i(x,\sigma) + 2(-1)^i \mu(\sigma)\sqrt{P_A^i(x,\sigma)P_B^i(x,\sigma)}\cos(2\pi\sigma x + \varphi)\,d\sigma$$

$$= \int_{band} \kappa_A^i(x,\sigma)P_A(x,\sigma) + \kappa_B^i(x,\sigma)P_B(x,\sigma) + 2(-1)^i \mu(\sigma)\sqrt{\kappa_A^i(x,\sigma)P_A^i(x,\sigma)\kappa_B^i(x,\sigma)P_B^i(x,\sigma)}\cos(2\pi\sigma x + \varphi)\,d\sigma$$

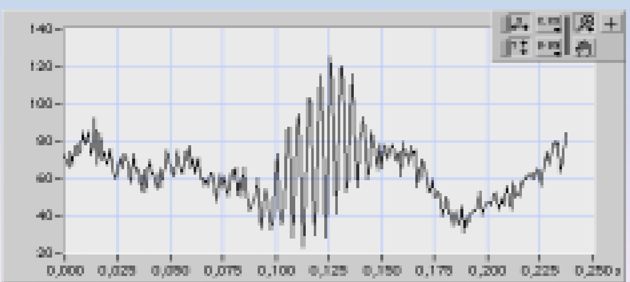
$$= P_A(x)\int_{band} \kappa_A^i(\sigma)B(\sigma)\,d\sigma + P_B(x)\int_{band} \kappa_B^i(\sigma)B(\sigma)\,d\sigma + 2(-1)^i\sqrt{P_A(x)P_B(x)}\int_{band}\sqrt{\kappa_A^i(\sigma)\kappa_B^i(\sigma)}\,\mu(\sigma)B(\sigma)\cos(2\pi\sigma x + \varphi)\,d\sigma$$

$$= \underbrace{P_A(x)\bar{\kappa}_A^i + P_B(x)\bar{\kappa}_B^i}_{I_{LF}(x)} + \underbrace{2(-1)^i\sqrt{P_A(x)P_B(x)}\sqrt{\bar{\kappa}_A^i\bar{\kappa}_B^i}\int_{band}\mu(\sigma)B(\sigma)\cos(2\pi\sigma x + \varphi)\,d\sigma}_{I_{HF}(x)}$$

Modulated part of the interferogram:

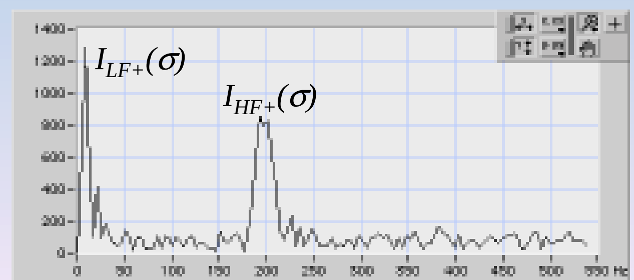
$$I_{HF}(x) = 2(-1)^i\sqrt{P_A(x)P_B(x)}\sqrt{\bar{\kappa}_A^i\bar{\kappa}_B^i}\int_{band}\frac{1}{2}\left[\mu(\sigma)B(\sigma)e^{2i\pi\sigma x+\varphi} + \mu(-\sigma)B(-\sigma)e^{2i\pi\sigma x-\varphi}\right]d\sigma$$

$$= (-1)^i\sqrt{P_A(x)P_B(x)}\sqrt{\bar{\kappa}_A^i\bar{\kappa}_B^i}\left[FT^{-1}\left\{\mu(\sigma)B(\sigma)e^{2i\pi\sigma x+\varphi}\right\} + FT^{-1}\left\{\mu(\sigma)B(\sigma)e^{2i\pi\sigma x+\varphi}\right\}\right]$$



Fourier

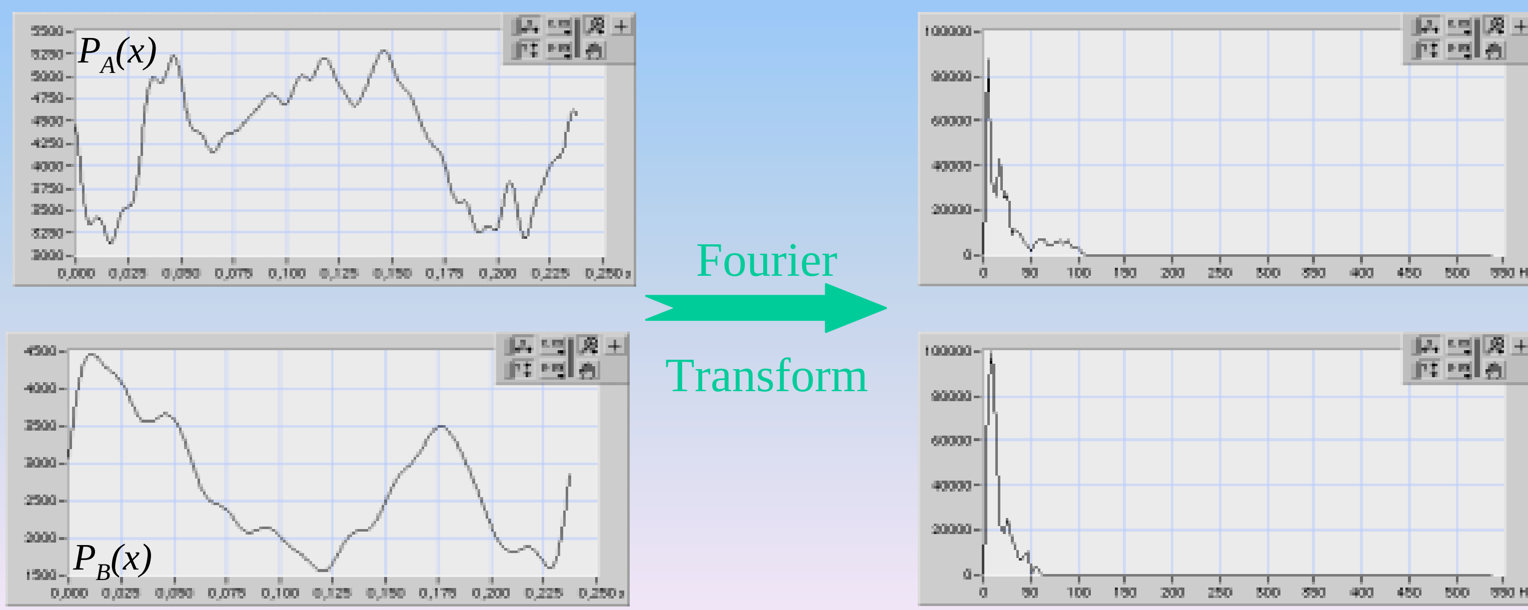
Transform



Computation of coherence factors

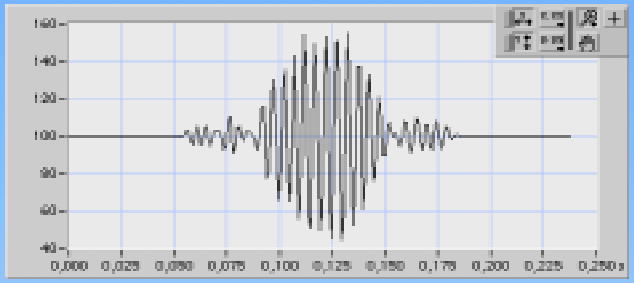
<u>1. Estimate κ matrix:</u> coefficients are determined by least-square fits of interferometric channels by photometric channels

<u>2. Estimate photometric signals:</u> signals are filtered by an optimum Wiener filter to minimize rms fluctuations but keep turbulent fluctuations



Computation of coherence factors

2. Derive the turbulence-corrected interferogram:



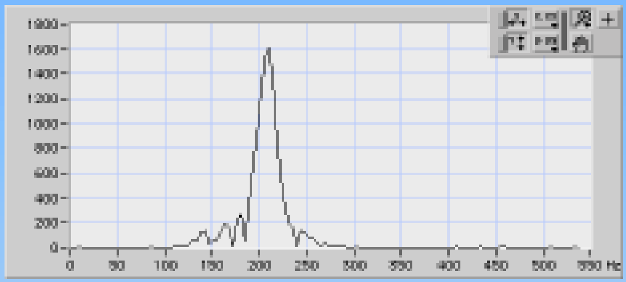
3. Estimate processed noise PSD:

Comment: the photon noise PSD should be subtracted too. It was not the case at the time of the R Leo observations because the photon bias was far below noise

Computation of coherence factors

4. Compute squared coherence factor:

Integrate corrected interferogram PSD

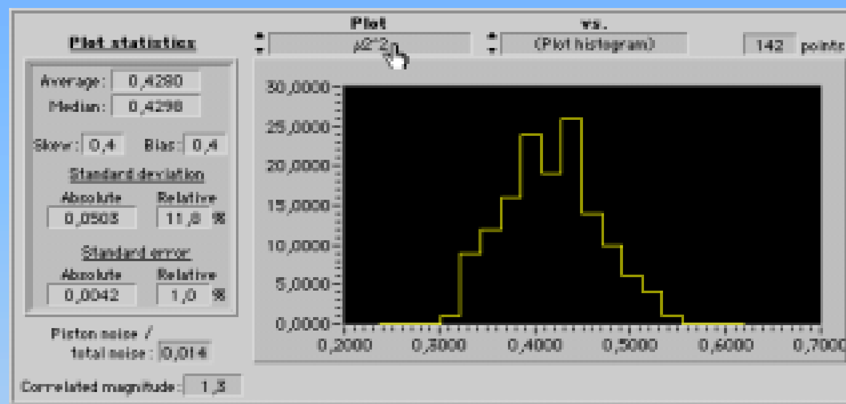


Subtract integrated processed noise PSD

That's it! You have computed the estimate of the squared coherence factor of one scan in one interferometric channel

Final estimate of the coherence factors

Squared coherence factors are computed for each scan per interferometric channel



They define a statistics (histogram) from wich a standard deviation is derived

Eventually one gets:

$$\mu_1^2 \pm \sigma\left(\mu_1^2\right)$$

$$\mu_2^2 \pm \sigma\left(\mu_{21}^2\right)$$

For more details on this algorithm see:

V. Coudé du Foresto et al., Astron. Astrophys. Suppl. Ser. 121, 379-392 (1997)

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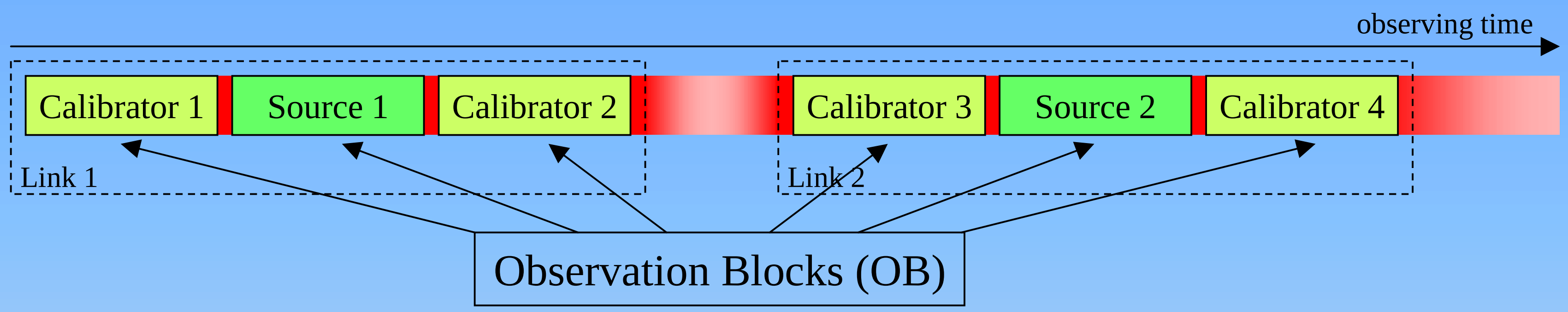
What needs to be calibrated?

Sources of coherence losses:

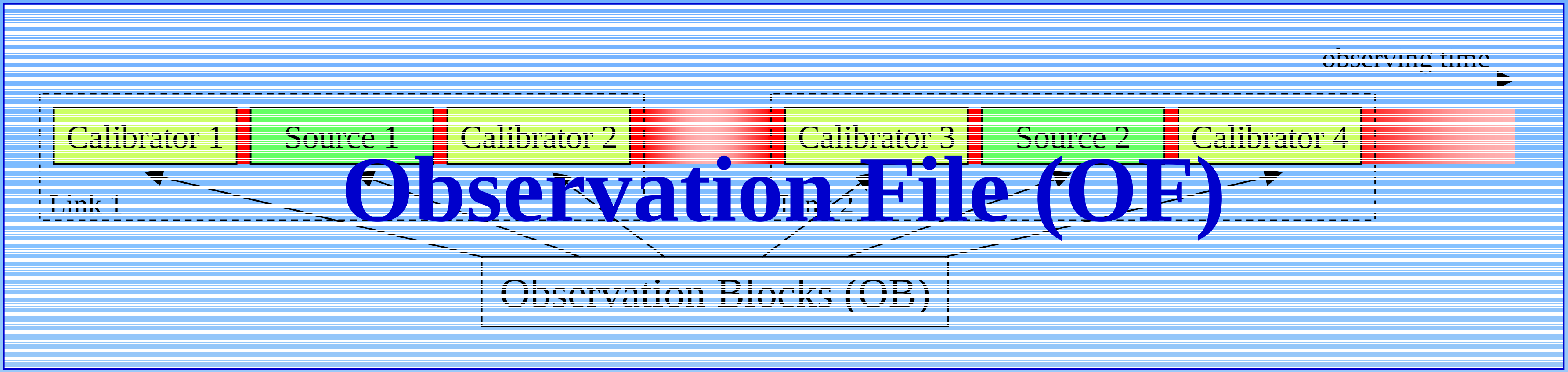
- polarization mismatches :
  - axes rotation
  - axes differential delay
- slow thermal drifts
- turbulence?

- differential piston?

Principles of the calibration



Principles of the calibration



- 1 OF = 1 set-up
  - same night
  - same detector parameters (frame rate, number of frames, ...)
  - same filter...

- Principle : follow slow coherence loss fluctuations

Steps

1. Derive calibrator's expected visibility

usually a uniform disk diameter is used to predict visibility at the spatial frequency *S*

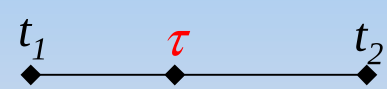
$$V_{\exp}(S) = \left| \frac{2J_1(\pi\theta_{UD}S)}{\pi\theta_{UD}S} \right|$$

2. Derive instantaneous transfer function for each channel

$$T_i^2(t_1) = \frac{\mu_i^2}{V_{\exp}^2(S)}$$

3. Interpolate transfer function at time when source was observed

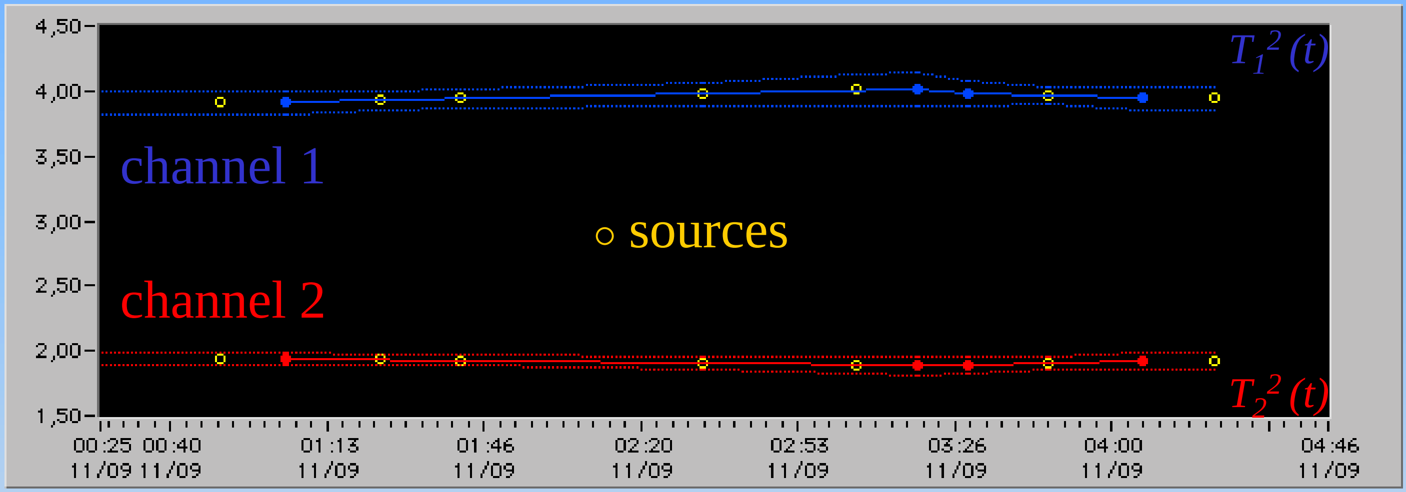
$$T_i^2(\tau) = \left(\frac{t_2-\tau}{t_2-t_1}\right) T_i^2(t_1) + \left(\frac{\tau-t_1}{t_2-t_1}\right) T_i^2(t_2)$$



4. Calibrate single channel visibility for science target

$$V_{ST,i}^2 = \frac{\mu_{ST,i}^2}{T_i^2(\tau)}$$

At this point, we have derived visibilities for each channel



Before deriving the final visibility estimate the important issues of associated error bars and correlations have to be looked in details

Propagation of errors

Sources of errors (1σ error bars):

- errors on coherence factors (detector noise, photon noise, piston noise)
- errors on the diameter of calibrators

Propagated errors:

- error on squared transfer functions: ratio of gaussian variables

the error is computed by estimating the 67% confidence interval of the random variable

- error on single-channel interpolated transfer functions:

the interpolation is equivalent to estimating the transfer function at τ by a least-squares fit. The error on the interpolated T is derived by varying a χ^2.

Propagation of errors

At this point, two visibilities V_1^2 and V_2^2 and their 1σ errors have been derived

These two estimates are not independent and part of the noise is correlated in the two channels:

- errors on calibrators diameters
- errors generated by seeing (photometric calibration, piston)

These correlations need to be taken into account for all the random variables considered so far.

The current output of the calibration procedure is therefore:

- two squared visibilities and associated errors: $V_1^2, V_2^2, \sigma_1, \sigma_2$
- correlation factor: ρ_{12}

Propagation of errors and final visibility estimate

The final visibility estimate is obtained by minimizing the quantity:

$$\chi^2(V^2) = \frac{1}{2}\begin{pmatrix} V_1^2 - V^2 \\ V_2^2 - V^2 \end{pmatrix}^t \begin{pmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 \\ \rho_{12}\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix}^{-1} \begin{pmatrix} V_1^2 - V^2 \\ V_2^2 - V^2 \end{pmatrix}$$

At minimum we have the following relations yielding the final visibility estimate and error:

$$\boxed{\begin{aligned} V^2 &= \frac{1}{\sigma_1^2 + \sigma_2^2 - 2\rho_{12}\sigma_1\sigma_2}\left[V_1^2\left(\sigma_2^2 - \rho_{12}\sigma_1\sigma_2\right) + V_2^2\left(\sigma_1^2 - \rho_{12}\sigma_1\sigma_2\right)\right] \\ \sigma_{V^2}^2 &= \frac{(1-\rho_{12}^2)\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2 - 2\rho_{12}\sigma_1\sigma_2} \end{aligned}}$$

Two-channel χ_{tc}^2:

$$\boxed{\chi_{tc}^2 = \frac{\left(V_1^2 - V_2^2\right)^2}{\sigma_1^2 + \sigma_2^2 - 2\rho_{12}\sigma_1\sigma_2}}$$

Special case: $\sigma_1 = \sigma_2 = \sigma \quad \Rightarrow \quad \sigma_V^2 = \frac{1+\rho_{12}}{2}\sigma^2$

Comment:

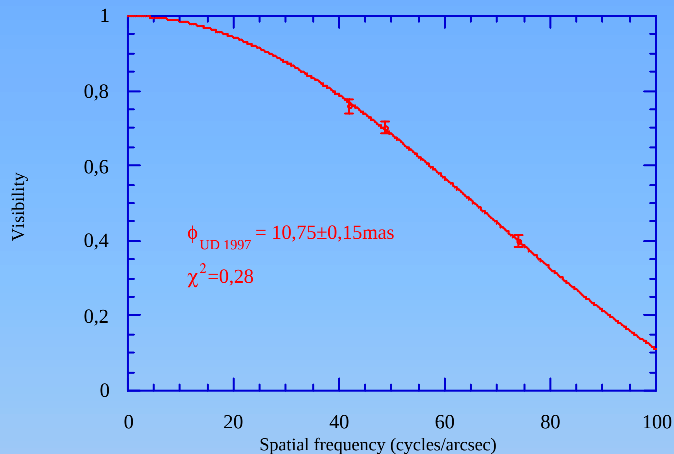
correlations between visibilities recorded at different times, with a different baseline,..., also have to be taken into account for model fitting.

In this case the (possible) correlation is due to the use of common calibrators (the expected visibilities are then correlated)

It is therefore necessary that the data reduction program outputs numbers necessary to compute the correlation *a posteriori*.

Have visibilities been well estimated?

BK Vir
Semi-regular variable of type M6.9 III



Best FLUOR visibility accuracy: 0,2%

Alpha Her
Super giant star of type M5 Ib

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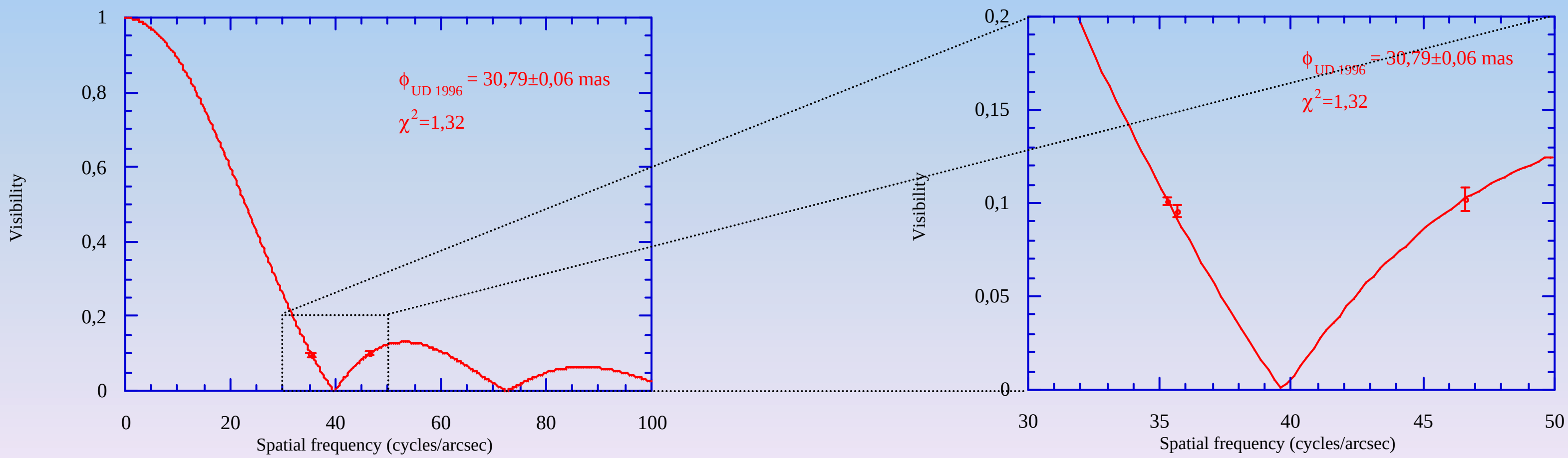
Super giant star of type M5 Ib



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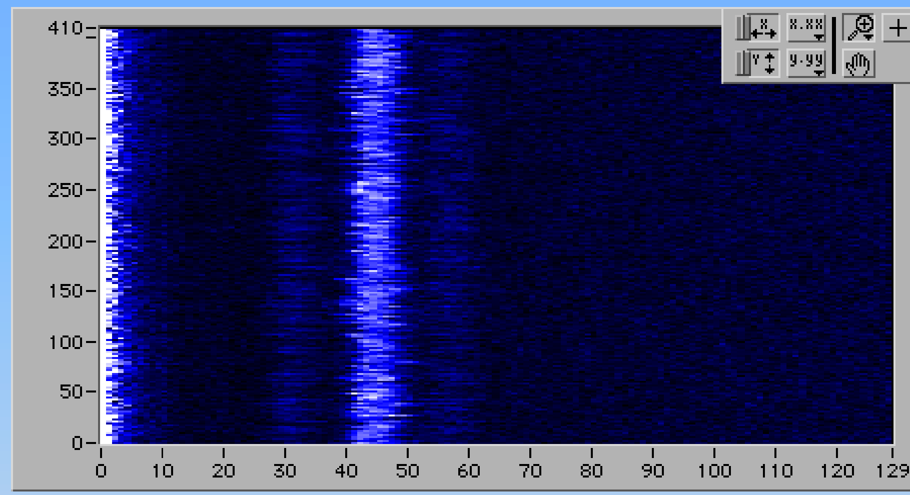
The calibration may not always be perfect for several reasons:

- gaussian statistics assumption fails

- vibrations

(visit museum of horrors!)



- too large piston fluctuations
- a visitor has been too curious and has touched the fibers
- bad genius of astronomical interferometry takes special care of you!
- others we still don't understand ...

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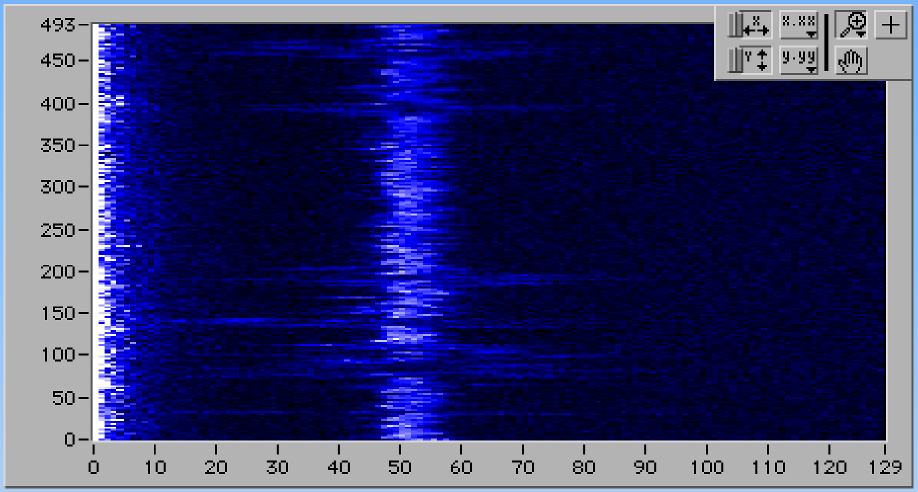

- too large piston fluctuations
- a visitor has been too curious and has touched the fibers
- bad genius of astronomical interferometry takes special care of you!
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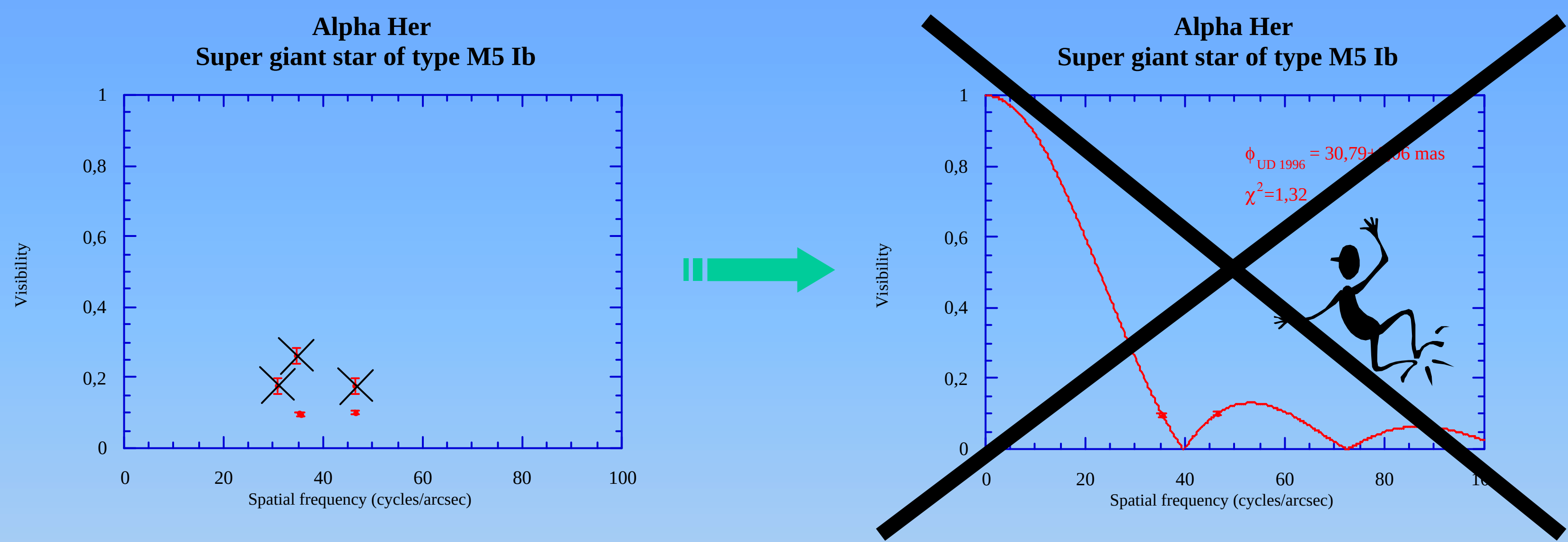
Tools are needed to objectively select visibility points in order to avoid this:



<u>Selection rules:</u>

-1. reject interferograms with vibrations (can be done during observations before saving an OB), sudden spikes, strange features ...

-2. reject batches with skew and bias of μ^2 distributions over certain limits (default values: skew=3σ, bias=2σ)

-3. reject visibilities for which the two channel χ_{tc}^2 is larger than 3: the two estimates are not compatible within 3σ

Selection rules (continued):

- 4. reject visibilities for which transfer function has fluctuated by more than x σ

These rules can be more or less stringent and can be adaptated depending on the science goal to achieve:

- very stringent for programs requiring high confidence and accuracy
    - stellar pulsation (Mira stars, Cepheids)
    - detection of surface features
    - direct exoplanet detection: precision level required few parts in few 10,000
- relaxed for easy programs (ex: diameter measurement)

Last rule: plot and fit visibilities only after pre-defined rules have been applied!

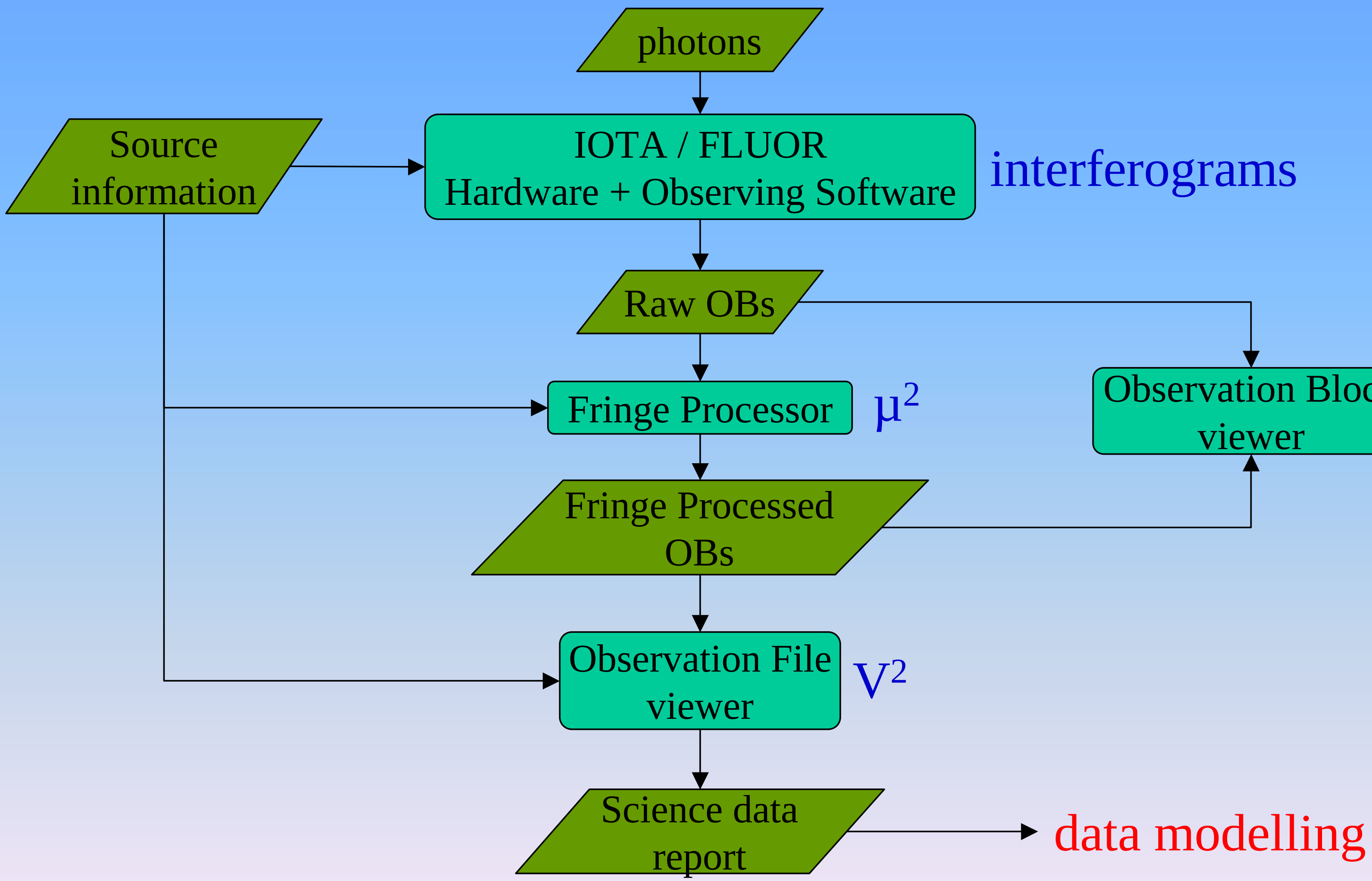
Part of the calibration algorithm and data selection procedure (except for the analysis of correlations) has been published in:

G. Perrin et al., Astronomy and Astrophysics 331, 619-626 (1998)

The analysis of correlations should be published soon as well as the algorithm to remove the photon noise bias.

You are ready for Lab Session Part II!

Dataflow



photons
Source information
IOTA / FLUOR Hardware + Observing Software
interferograms
Raw OBs
Fringe Processor
μ2
Observation Block viewer
Fringe Processed OBs
Observation File viewer
V2
Science data report
data modelling